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Technological and Engineering Aspects of the Development of Biogas and Biomethane Plants in Ukraine: Prospects for Integration into the Country's Energy System

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Abstract

The study is aimed at identifying key technical solutions and opportunities for using biogas and biomethane to improve the efficiency and stability of the Ukrainian energy system. This study analysed the raw material sources for biogas production, fermentation processes and integration of biogas plants into the power grid. The study found that the use of biogas and biomethane plants contributes to the energy independence of Ukraine. The main sources of raw materials were identified, including agricultural waste, organic residues from the food industry and energy crops. The analysis showed that biogas plants can stably produce fuel for energy generation, which makes it possible to balance fluctuations in the operation of renewable energy sources, in particular solar and wind power plants. The article proves the effectiveness of the introduction of cogeneration plants that provide not only electricity but also heat for industrial or municipal needs. It is also found that modern biogas purification technologies, such as membrane separation and absorption, allow the production of biomethane, which corresponds to natural gas in terms of its characteristics. An assessment of the prospects for integrating biomethane into the Ukrainian gas transmission system has shown the possibility of using this fuel as an environmentally friendly analogue of fossil gas. The results of the study emphasise the importance of government support and infrastructure development to enhance the implementation of biogas technologies. It has been established that the combination of biogas plants with energy storage systems can increase the stability of electricity supply to the grid, which is especially important for regions with uneven energy consumption. In addition, it has been confirmed that the creation of local energy clusters based on biogas plants helps to reduce dependence on imported energy resources and develop rural areas.

Keywords

Agricultural waste; Cogeneration; Membrane separation; Absorption; Renewable energy

Introduction

In the context of global climate change and the need to reduce greenhouse gas emissions, the use of renewable energy sources is becoming increasingly important for many countries, including Ukraine. Biogas and biomethane, which can be produced from organic waste, are among the most promising sources of clean energy. Not only do they help reduce dependence on fossil fuels, but they also reduce the negative impact on the environment, increase the efficiency of agricultural waste use and open up new prospects for the development of regional economies. Biogas and biomethane production in Ukraine have significant potential for integration into the national energy system, but several technical and engineering challenges need to be overcome to make it happen. This includes improving anaerobic digestion processes, biogas purification and adapting the infrastructure for biomethane production. The successful implementation of these technologies can contribute to the sustainable development of the energy sector, the formation of local energy clusters and the reduction of CO_2 emissions.

The problem of introducing biogas and biomethane technologies is relevant due to the need to reduce dependence on traditional energy resources and achieve energy sustainability. Yusuf and Almomani (2022) investigated the use of membrane technologies for biogas purification, focusing on their efficiency and potential for producing high-quality biomethane. Their work proved that these technologies can significantly improve purification standards and meet the requirements of European regulations. Swinbourn, Li, and Wang (2024) analysed the economic aspects of biogas plants, taking into account the costs of construction and operation of such projects. They assessed the profitability and payback periods, which have become important factors for expanding the use of biogas technologies. Iqbal *et al.* (2021) analysed the social benefits of biogas plants, in particular their positive impact on job creation in rural areas. They noted that the development of such projects can be a key factor in the economic growth of rural areas. Chew *et al.* (2021) studied anaerobic fermentation technologies, in particular hydrolysis and methanogenesis, to improve the efficiency of biogas production. They proposed new approaches to controlling fermentation conditions to increase the energy yield per unit of feedstock. Lehtoranta *et al.* (2024) studied the impact of biogas plants on reducing greenhouse gas emissions, assessing the effectiveness of such technologies in the context of global warming. They proposed methods for assessing the environmental impact of biogas projects, which could become an important tool for climate change policy.

Prussi *et al.* (2020) focused on the possibilities of integrating biomethane into gas transmission systems by analysing the existing infrastructure for this purpose. Their study identified the benefits and challenges that stood in the way of introducing biomethane into the energy system. Bednarek, Klepacka, and Siudek (2023) studied the obstacles to the development of agricultural biogas plants, including high initial investment and insufficient legal regulation. They found that the integration of biogas technologies into existing energy and agricultural systems faces challenges that hinder their practical implementation. Heiker *et al.* (2021) investigated the use of biogas plants to ensure energy independence from external energy suppliers. They argued that the implementation of such projects could significantly reduce energy dependence and increase the stability of energy systems. Sulewski *et al.* (2023) analysed the experience

of European countries in using biomethane as an alternative to natural gas. They studied legislative and technical regulations and suggested opportunities for adapting European models to the realities of other countries. Kabeyi and Olanrewaju (2022) examined the engineering aspects of biogas plant design, focusing on the choice of materials to ensure their durability and efficiency. They also provided recommendations for optimising technological processes to ensure high performance and lower operating costs. Gaps requiring further study include the impact of changing technology costs in the long term, the effectiveness of regional initiatives to support biogas projects, and the adaptation of engineering solutions to different operating conditions.

The purpose of this study is to provide a comprehensive review of the current state of biogas and biomethane technologies in Ukraine, assessing their potential for integration into the national energy system.
The specific objectives were:

1. To analyse the efficiency of various biogas purification technologies and their effects on biomethane quality.
2. To explore the feasibility of integrating biomethane into national energy systems as a means to strengthen energy autonomy.
3. To assess the economic viability of biogas projects, focusing on construction and operational costs.

Materials and Methods

This study employed a qualitative engineering research method, which involved the synthesis and comparative analysis of technical, economic, and environmental data from previous scientific publications, project reports, and technical documentation on biogas plants in both Ukraine and the EU. The primary aim was to identify the most efficient technological configurations and methods for integrating biogas and biomethane plants into the Ukrainian energy system. Specific technical solutions, alternative feedstocks, treatment technologies, and integration models were evaluated from a system-level perspective. To ensure a robust and comprehensive analysis, the literature selection for this study adhered to clearly defined inclusion and exclusion criteria. Only peer-reviewed articles, technical reports, and case studies published within the last 10 years were included to ensure the relevance and currency of the information.

Studies that provided data on the technological efficiency, economic feasibility, and environmental impact of biogas and biomethane plants; studies focused on biogas plant operations in both agricultural and industrial contexts; and publications that discussed the integration of renewable energy sources into national power grids were included in the study. Articles that focused exclusively on non-renewable energy sources, studies with inadequate data quality or methodological transparency, and reports with limited applicability to the Ukrainian context were excluded. Databases such as Scopus, Web of Science, and Google Scholar were searched to identify relevant studies. Keywords used for the literature search included “biogas purification,” “biomethane production,” “biogas plant integration,” and “EU renewable energy systems.”

The study placed particular emphasis on EU case studies, given the region’s advanced development and implementation of biogas and biomethane technologies. These

countries have a long history of integrating renewable energy sources, particularly biogas, into their national grids. EU countries, such as Germany and Denmark, offer valuable lessons due to their established infrastructure, advanced regulatory frameworks, and successful integration of biogas plants with renewable energy systems like wind and solar. Their experience provides important insights that can be adapted to the Ukrainian context, where similar technological and infrastructural challenges may arise. By focusing on these case studies, the study aimed to derive transferable best practices and identify challenges that Ukraine may face in scaling up its biogas and biomethane production.

The relevance of these case studies lies in the fact that both Ukraine and the EU share certain economic and agricultural characteristics, particularly in terms of their agricultural output, which makes the findings from the EU applicable to Ukraine's renewable energy development strategies. Furthermore, EU case studies provide a benchmark for assessing the technological, economic, and regulatory aspects of biogas plants, all of which are crucial for Ukraine's transition to renewable energy.

The assessment of biogas and biomethane integration was organised into three interrelated thematic areas: technological efficiency, energy system integration and economic feasibility. The technological efficiency was assessed by analysing anaerobic digestion processes, treatment methods and engineering solutions, including modular plant configurations. Particular attention was paid to the applicability and scalability of these technologies in the climatic and infrastructural conditions of Ukraine. The integration of energy systems emphasises the compatibility of biogas plants with existing gas transmission networks and their ability to work together with intermittent renewable energy sources such as solar and wind power. The function of biogas plants in balancing energy supply during periods of peak demand or reduced generation from alternative sources has been scrutinised. Economic viability was assessed by combining data on capital investment requirements, operating costs, energy revenues, and projected payback periods. The integrated sustainability of these technologies was assessed by analysing their socio-economic effects, including job creation, rural development, and their contribution to environmental objectives by recycling organic waste and reducing greenhouse gas emissions.

Results

The development of biogas projects in Ukraine is an important step towards energy independence and the introduction of renewable energy sources. With its significant agricultural potential, Ukraine can effectively use biogas technologies to process organic waste and specially grown energy crops. However, despite favourable conditions, the industry remains underdeveloped and requires comprehensive solutions to scale up.There are more than 50 biogas plants in Ukraine, most of which are concentrated in the central and western regions. They operate mainly on livestock and crop waste, as well as on raw materials from the food industry. Biogas plants are used both on large agricultural enterprises and on small farms (Golub *et al.*, 2017). However, their share in the country's overall energy balance remains insignificant, accounting for less than 2% of all renewable energy sources. The main reasons for the slow development are complex

project approval procedures, insufficient financial support, and limited investor awareness of the economic benefits of biogas technologies (Martyn *et al*., 2024).

Ukraine has a biogas production potential of approximately 8 billion cubic metres per year. If this resource is fully utilised, biogas plants could provide up to 10% of domestic natural gas consumption. This would not only help reduce dependence on fossil fuel imports but also increase the country's energy security. To realise this potential, it is necessary to establish an effective organic waste collection system and create favourable conditions for growing energy crops (Artemenko *et al*., 2025). The main sources of feedstock for biogas plants are livestock waste (cattle and pig manure), crop waste (straw, corn, and beet residues), and organic waste from the food industry. In addition, specially grown energy crops, such as corn, sorghum and alfalfa, are of great interest. They have high yields and a stable chemical composition, which ensures predictable efficiency of fermentation processes. The introduction of such crops into the crop rotation will not only generate additional energy sources but also improve soil fertility through organic fertilisers that remain after anaerobic fermentation.

The further development of the biogas industry in Ukraine requires improved government policy, including the introduction of financial support mechanisms, tax benefits and co-financing programmes with international organisations. It is also relevant to strengthen the information campaign on the benefits of biogas technologies among farmers and businesses. In addition, it is necessary to stimulate the introduction of innovative solutions that will increase the efficiency of raw material processing and reduce the capital costs of building biogas plants. Thus, biogas projects have significant potential for development in Ukraine, which will not only reduce dependence on traditional energy resources but also improve the environmental situation through the disposal of organic waste. The successful implementation of these projects depends on a comprehensive approach that includes government support, active participation of businesses and the use of modern technologies in biogas production. Biogas and biomethane production are based on the use of a variety of organic feedstocks that are available in many regions and can ensure the efficiency of anaerobic fermentation processes. The main sources of feedstock include agricultural waste, organic waste from the food industry, municipal wastewater treatment plants, and energy crops (Mignogna *et al*., 2023).

Agricultural waste is an important feedstock for biogas production (Lyubchyk *et al*., 2015). The most common of these are manure, silage, and crop residues. Manure, in particular cattle manure, is a rich source of organic matter that actively decomposes under anaerobic conditions, providing a stable biogas yield. To increase the efficiency of the fermentation process, silage is added to bioreactors, especially corn silage, which is a high-quality source of carbohydrates that stimulates intensive decomposition. In addition, crop residues such as straw or vegetable residues can also be used in biogas production processes. However, they usually need to be prepared for this purpose, as their composition may be less amenable to fermentation compared to other feedstocks (Frankowski and Czekała, 2023). Another important source of feedstock is organic waste from the food industry, which includes fruit and vegetable residues, meat and dairy products, as well as food waste from restaurants and supermarkets. These wastes have a high concentration of carbohydrates, proteins and fats, making them suitable for anaerobic digestion. They can also contribute to increasing the energy potential of the

biogas produced during the process. Recycling such waste also helps to reduce the amount of organic waste that can pollute the environment and reduces the need to dispose of it in landfills (Nabgan *et al*., 2021).

Wastewater sludge generated at municipal wastewater treatment plants is another promising source of feedstock for biogas production. This sludge contains a significant amount of organic matter that undergoes anaerobic digestion, contributing to energy production. An important advantage is that the use of such waste allows not only to produce biogas, but also to solve the problem of sewage sludge disposal, reducing the burden on landfills and reducing the environmental risks of soil and water pollution (Hurynovich, Kwietniewski, and Romanovski, 2021). Energy crops grown specifically for biogas production have high yields and a stable chemical composition, which ensures the predictable efficiency of fermentation processes (Kubiczek *et al.,* 2023). Corn, sorghum, and alfalfa are particularly popular among these crops. Corn, due to its high starch content, is one of the key sources of feedstock for biogas plants (Shahini *et al.,* 2023). These crops are grown in agricultural areas where land can be used efficiently for energy production. However, the impact of energy crops on the land balance and environmental conditions needs to be taken into account, and effective coordination between food and energy production needs to be ensured (Gadirli *et al*., 2024). The diversity of feedstocks for biogas and biomethane production allows for adaptation of technologies to specific regional conditions and maximum use of available local resources. Agricultural waste, organic residues from the food industry, sewage sludge, and energy crops are key feedstocks that ensure both economic and environmental efficiency of biogas plants (Lyubchik *et al.,* 2008; Muminova *et al.,* 2023). Further development of this industry requires continuous improvement of feedstock processing technologies and the formation of stable production chains focused on maximising the use of local resources and minimising negative environmental impact.

Biogas purification is a key step in the biomethane production process, as it ensures the achievement of high-quality gas suitable for use as an alternative energy source. Depending on the purification technology used, different levels of efficiency and reduction of impurities such as hydrogen sulphide, carbon dioxide and moisture can be achieved. Since biomethane is analogous to natural gas, its quality must meet certain standards for efficient use in energy and industrial applications. Table 1 shows a comparison of the main biogas purification methods, such as membrane separation, absorption and cryogenic distillation, in terms of their efficiency and impact on the final biomethane quality.

The production of biogas and biomethane is a complex multi-stage technological process that involves biochemical and physical transformations of organic raw materials (Kucher *et al.,* 2022). This process not only contributes to the generation of renewable energy but also allows for the efficient disposal of organic waste, which is important for sustainable development. Anaerobic fermentation is a biochemical process that includes four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Initially, complex organic molecules such as proteins and carbohydrates are broken down into simpler compounds. These compounds are then converted into organic acids, hydrogen and carbon dioxide. In the process of acetogenesis, organic acids are converted to acetic acid and hydrogen, and in the final step, methanogens produce methane and carbon dioxide. Methane is a

valuable energy carrier due to its high calorific value, which makes this process important for biogas production (Rafiee *et al*., 2020). To ensure high efficiency of biogas production, it is necessary to maintain optimal temperature conditions. Depending on the type of bioreactor, mesophilic (32-42°C) or thermophilic (50-60°C) conditions can be used. The mesophilic mode ensures a stable biochemical decomposition of organic matter at moderate temperatures, while the thermophilic mode promotes faster decomposition and higher gas volumes, but requires additional energy costs due to the need to maintain high temperatures (Wang *et al*., 2022). Monitoring the pH level is a key element of the process. The optimal pH range of 6.8 to 7.5 is essential for maintaining the activity of methanogenic bacteria during the anaerobic digestion process. If the pH decreases, organic acids can be formed, which inhibit the activity of methanogenic microorganisms. Therefore, regular pH monitoring and timely correction are essential to maintain stable biogas production (Maurus *et al*., 2021).

Table 1: Comparison of biogas purification technologies in European and Ukrainian contexts

Cleaning technology	*Technology description*	*Cleaning efficiency (%)*	*Impact on biomethane quality*	*Advantages*	*Disadvantages*
Membrane separation	Using membranes to remove CO_2, water and hydrogen sulphide	90-99%	High purity of biomethane, minimal content of impurities	High efficiency, low operating costs	High installation and maintenance costs
Absorption (chemical method)	Using liquid absorbers to capture CO_2 and hydrogen sulphide	80-95%	Improving gas quality, reducing CO_2 and H_2S content	High efficiency for large volumes	High operating costs, the need to replace absorbers
Cryogenic distillation	Biogas purification using low temperatures for CO_2 condensation	95-99%	Very high degree of purification, almost free of impurities	High efficiency, suitable for large volumes of biogas	High energy costs, expensive installations
Adsorption on activated carbon	Absorption of CO_2 and hydrogen sulphide impurities on the surface of the adsorbent	85-95%	Improving the purity of biomethane, reducing hydrogen sulphide	Simplicity of technology, low cost of equipment	Limited effectiveness, requires frequent replacement of the adsorbent

Source: Atelge *et al*. (2021)

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Mixing of the organic feedstock is also crucial for an efficient process. Regular mixing promotes uniform contact of bacteria with organic matter, which prevents the formation of stagnant zones and ensures stable decomposition of organic matter. In addition, mixing improves the availability of nutrients for microorganisms, which increases biogas yields. After biogas is produced, it is purified from impurities such as hydrogen sulphide, carbon dioxide and moisture. This is an important stage as it produces biomethane, a high-quality analogue of natural gas that can be used for energy or transportation purposes. Modern purification technologies include membrane separation, absorption and cryogenic distillation. Membrane separation allows for the efficient separation of CO_2 from methane using special membranes. Absorption involves the absorption of unwanted gases by special liquids such as amines, while cryogenic distillation separates gases by using low temperatures.

Thus, the biogas and biomethane production process is a complex system consisting of several interconnected stages. Each stage requires detailed control and maintenance of optimal conditions to achieve high efficiency. The use of modern technologies allows us to improve the quality and volume of biogas produced, reduce the environmental impact and ensure a stable supply of renewable energy. Integration of biomethane into national energy systems is an important step towards ensuring energy security and independence. Biomethane, as a renewable energy source, can become an alternative to traditional fossil fuels, which will help reduce dependence on imported energy resources. For the effective integration of biomethane into the energy system, technical, economic and regulatory aspects need to be taken into account. Table 2 shows different scenarios of biomethane integration into the energy system, which allows us to assess the potential of this technology to enhance energy independence at the local, national and international levels.

Table 2: Potential for integrating biomethane into energy systems to increase energy independence

Integration approach	*Description*	*Potential for energy independence*	*Advantages*	*Challenges and limitations*
Integration with national gas networks	Supply of purified biomethane to the general gas network	Increasing the stability of the energy supply, reducing dependence on gas imports	Export of biomethane, use of existing gas network infrastructure	The need for biomethane certification, high investments in infrastructure
Installation of autonomous biogas plants	Using biogas at the local level to meet the energy needs of communities	Increasing energy independence for rural areas and businesses	Reducing electricity costs, creating new jobs	Limited capacity of installations, dependence on the availability of raw materials
Combining with other renewable sources	Integration of biogas plants with solar or wind stations to	Increasing the stability of the energy system, using biogas to	High energy efficiency, possibility of	Dependence on weather conditions for solar and

Integration approach	*Description*	*Potential for energy independence*	*Advantages*	*Challenges and limitations*
	create a comprehensive energy system	compensate for interruptions in other energy sources	production regulation	wind energy sources
Creation of local energy clusters	Combining several biogas plants to meet energy needs at the regional or city level	Promoting energy independence for large areas, reducing energy costs	Stable and efficient use of biomethane at the local level	High capital cost of construction, need for coordination between different projects

Source: Karaca, Dincer and Nitefor (2022)

The introduction of biogas plants into modern energy systems requires a comprehensive approach to engineering solutions that takes into account regional specifics, available technical capabilities and requirements for the stability of energy supply. The efficiency of using biogas as an energy source depends on the optimal combination of technological flexibility, innovative approaches and careful planning. One of the key approaches is the use of modular biogas plants (Figure 1). Modularity makes it easy to scale up capacity depending on the amount of feedstock available and the requirements of specific consumers. In rural areas, such plants can supply electricity to small farms with relatively low energy needs. In industrial areas or densely populated regions, large modular plants with high performance can be installed to supply energy to large enterprises or numerous residential areas. The modular approach makes it possible to quickly adapt the system to changing conditions and change the capacity without significant additional infrastructure costs.

To ensure a stable supply of energy to the grid, it is important to combine biogas plants with energy generation and storage systems (Naumenkova *et al.*, 2024). The use of batteries or other energy storage methods can smooth out fluctuations in energy supply that may occur due to the variability of biogas production. Such an energy storage system stores excess electricity generated at times of low consumption and supplies it to the grid during peak loads, when electricity demand is highest. This increases the reliability of the power system, making biogas competitive with traditional energy sources. The combination of biogas plants with other renewable energy sources, such as solar and wind power plants, is another promising opportunity. The combination of these technologies allows for the creation of integrated energy solutions that can ensure a stable supply of energy even in adverse weather conditions. For example, at night or during windless periods, biogas plants can compensate for the decrease in electricity production from solar or wind power plants, ensuring a continuous and stable energy supply. This approach is particularly effective in regions where weather conditions can be unstable and cause significant fluctuations in energy supply.

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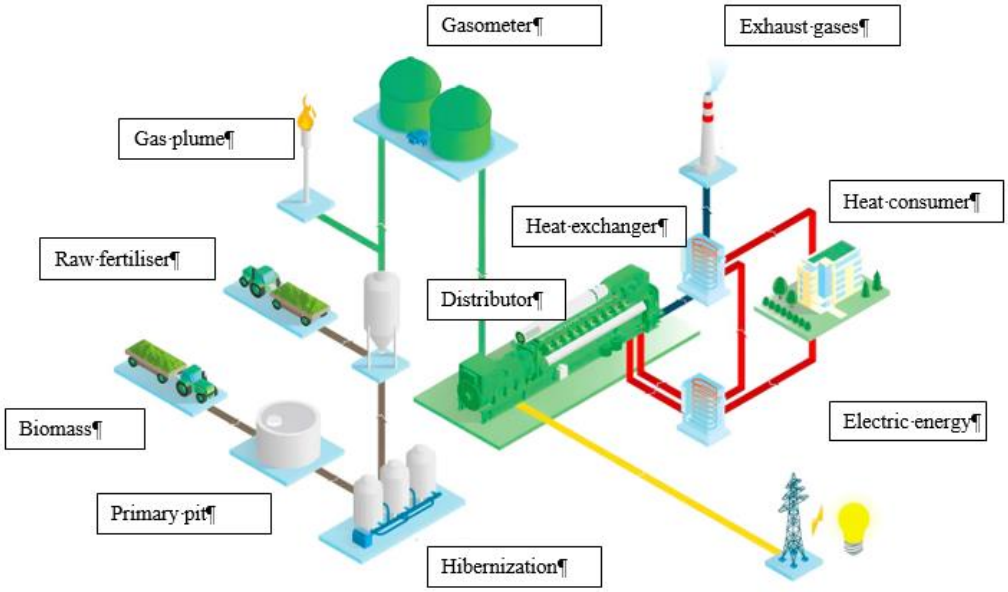

Figure 1: Biogas plant for cogeneration

Cogeneration plants are also important for integrating biogas technologies into the grid (Figure 2). They provide simultaneous production of electricity and heat, which significantly improves the overall efficiency of the plants. The thermal energy generated in the biogas production process can be used for heating production facilities or technological processes at enterprises. This makes biogas plants particularly beneficial for industrial enterprises, as they not only provide energy but also reduce the cost of heating and other heat energy needs.

Therefore, engineering solutions for the integration of biogas plants into the power system are based on a comprehensive and innovative approach that includes modular plants, energy storage, combination with other renewable energy sources and the use of cogeneration technologies. The implementation of these solutions contributes to the development of sustainable energy systems, reduces dependence on fossil fuels and ensures environmental safety at the local and global levels. Biogas and biomethane are becoming increasingly popular in the modern electricity sector due to their environmental benefits and ability to integrate into various energy systems (Smagulova *et al.,* 2018). They are important renewable energy sources that contribute to sustainable development, reduce dependence on fossil fuels and reduce the negative impact on the environment. The use of biogas and biomethane in electricity production has several key aspects that determine their role in power systems (Negro, Noussan, and Chiaramonti, 2024). One of the key functions of biogas and biomethane in the electricity sector is their role as backup energy sources. This becomes especially important when other renewable sources, such as solar or wind power plants, show unstable electricity production due to changes in weather conditions. Biogas plants ensure the stability of energy supply by filling gaps in production when other sources cannot operate at full capacity (Borisov *et al.,* 1987). This is especially important for maintaining the balance in power systems where the share of renewable energy sources is significant. In this way, biogas and biomethane help make energy systems more reliable and flexible.

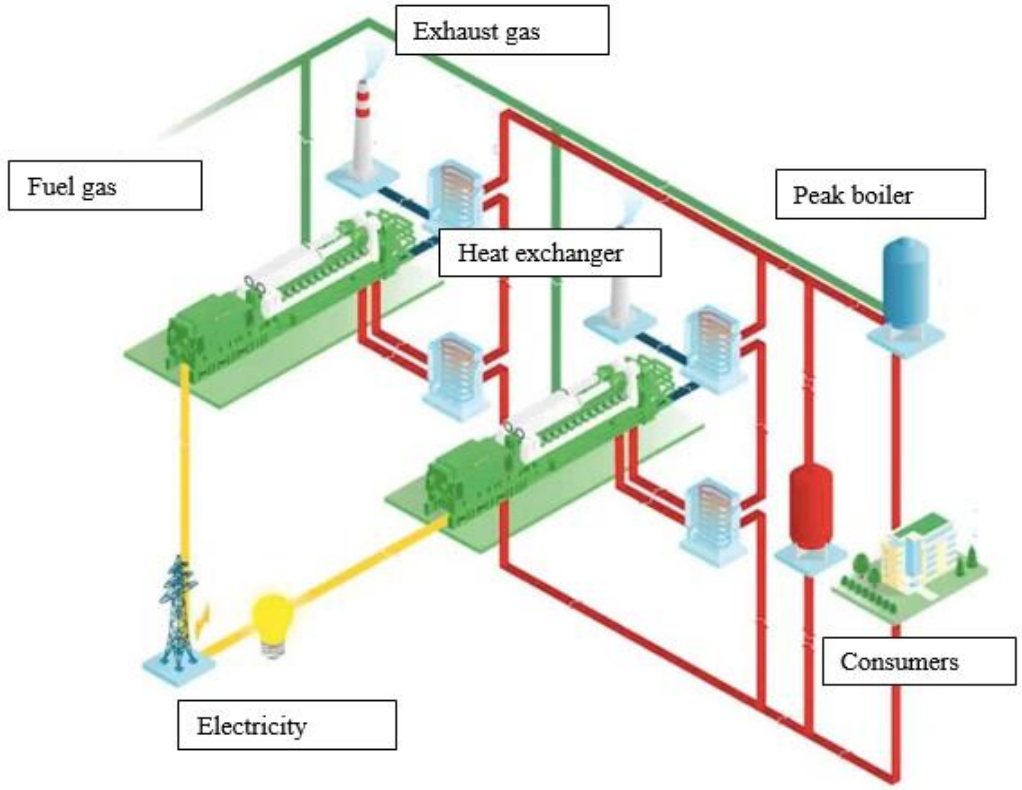

Figure 2: Cogeneration plant

In Ukraine, a successful biogas project has been implemented in the Lviv region that processes organic waste from agriculture and the food industry (Dudin et al., 2024). The biogas plant in Lviv serves as an example for other regions, using agricultural waste such as manure and crop residues to produce biogas. This project has demonstrated the potential of biogas to reduce dependence on fossil fuels, as well as provide a solution for organic waste management. The plant also uses cogeneration technology to supply electricity and heat to local communities, contributing to energy security. However, the project has faced challenges related to regulatory approvals and financing, highlighting the need for streamlined processes and government support to scale up such projects across Ukraine.

In the EU, Germany has long been a leader in biogas production thanks to strong government support and a clear regulatory framework (Jutteau, 2022). The Biomass Energy Directive provides favourable feed-in tariffs and other financial incentives, creating a thriving market for biogas and biomethane production. A key example is the city of Bad Werischofen, where a decentralised biogas plant not only processes local agricultural waste but also integrates into the national gas grid, providing both renewable energy and waste management solutions. This integration model in Germany shows how biogas can complement other renewable energy sources, such as wind and solar, and stabilise the grid. The German experience emphasises the importance of clear certification processes and incentives to overcome barriers to biogas deployment.

The use of biogas and biomethane is also important for reducing greenhouse gas emissions, which are one of the main causes of global warming. Biogas production is part of the natural carbon cycle and helps prevent additional carbon dioxide from being released into the atmosphere (Hamidova, Huseynov, and Samadova, 2022). When biogas is burned to produce electricity, carbon dioxide absorbed by plants during photosynthesis is released, making the process carbon-neutral. Biogas plants also allow for the disposal of organic waste, which can decompose in landfills and emit methane, another potent greenhouse gas. Thus, biogas plants not only produce energy but also have a positive impact on the environment by reducing methane emissions into the atmosphere. Another important aspect is the creation of local energy clusters that support the energy independence of rural areas. The production and use of biogas directly in the regions helps to reduce dependence on centralised energy suppliers, which is especially important for remote or rural areas where access to traditional energy sources may be limited. This allows local communities not only to receive a stable energy supply, but also to create new jobs, develop infrastructure and strengthen economic potential. Thus, biogas and biomethane perform an important function in the electricity sector, ensuring the stability of energy supply, reducing greenhouse gas emissions and contributing to the development of local economies. They significantly contribute to the sustainable development of energy systems, reducing dependence on fossil fuels and ensuring environmental safety.

Biogas projects require significant investment, but they can bring significant financial benefits in the future due to their energy and environmental benefits (Ismayilov *et al.*, 2023). The analysis of the economic efficiency of such projects includes an assessment of the costs of construction, operation and possible revenues from the sale of biogas or biomethane. Consideration of various economic indicators, such as the cost of investment, project payback period and revenue level, is important for determining the profitability of projects. Table 3 provides a comparison of the different aspects of economic evaluation, which helps to identify the potential benefits and risks for investors in biogas technologies.

Table 3: Assessment of economic indicators of biogas project implementation

Parameter	*Description*	*Cost (thousands USD)*	*Region-Specific Considerations*	*Potential Benefits*
Costs of Building the Plant	Includes equipment purchase, fermenter construction, and purification systems	500 - 3000	High initial capital costs are influenced by the level of regional development and proximity to existing infrastructure. In central and western Ukraine, where agricultural activity is more prevalent, costs may be lower	Essential infrastructure for biogas production; enables energy security and waste management.

Parameter	*Description*	*Cost (thousands USD)*	*Region-Specific Considerations*	*Potential Benefits*
			due to easier access to raw materials and logistical support.	
Operating Expenses	Maintenance costs, electricity, working materials, and salaries	50 - 150	Regions with higher agricultural output may benefit from reduced feedstock transportation costs. However, remote areas with inadequate infrastructure may see higher operational costs due to logistical challenges.	Stable operating costs with potential for local job creation, contributing to regional economic growth.
Expected Profit	Revenues from the sale of electricity and biomethane	200 - 1000	Ukraine's feed-in tariffs for renewable energy, such as biogas, incentivise the sale of energy. For regions benefiting from EU funding or subsidies, profits may increase as a result of additional financial support.	Enhanced profitability through long-term stable revenue streams, particularly with government incentives.
Payback Period	Time required for a full return on investment	5 - 10 years	The payback period can be shortened with the integration of EU funding opportunities or subsidies provided by the Ukrainian government. In regions with strong support for renewable energy, such as through tax benefits or grants, the payback period may be reduced.	Shorter payback periods, driven by governmental financial support, are enhancing investment attractiveness.

Parameter	*Description*	*Cost (thousands USD)*	*Region-Specific Considerations*	*Potential Benefits*
Biogas Purification Costs	Cost of the biogas purification process to biomethane (including technology and energy)	0.02 - 0.1 USD/m³	The availability of EU funding for renewable energy technologies could lower purification costs. Furthermore, subsidies provided by Ukraine's government could reduce the burden on producers by offering financial support for purchasing purification technologies.	Reduced costs of purification technologies improve the overall efficiency of biogas production.

Source: Trypolska *et al.* (2021)

The prospects for the development of biogas and biomethane technologies offer great potential for creating a sustainable energy future (Rogovyi, 2018). Given the environmental and economic benefits of these technologies, it is necessary to create conditions for their implementation, including economic incentives, technical integration and innovative approaches. One of the key areas of development is the introduction of incentive tariffs and preferential conditions for the construction of new biogas and biomethane plants. Such financial support mechanisms can significantly reduce capital expenditures for project implementation, increase investment attractiveness, and ensure a stable return for investors. One of these effective initiatives is the Renewable Energy Directive (RED II), which operates within the European Union and supports the financing of biogas and biomethane projects. This programme can be adapted for implementation in other regions, which will promote the development of the industry and reduce the cost of energy projects (Mai-Moulin *et al*., 2020).

The integration of biomethane into the European gas network is another key step in the development of this technology. Biomethane certified according to European standards can be supplied to the general gas network, which increases the economic viability of projects and opens up new export opportunities. This helps to strengthen positions in the international energy market, attract additional investments and promote the development of energy clusters at the local level. Taking these aspects into account not only reduces transportation costs but also increases the economic efficiency of biomethane use. The integration of biogas and biomethane technologies into the Ukrainian energy system faces several challenges specific to the region, including gaps in the regulatory framework and infrastructure, as well as limited financial support for new projects. While biogas has significant potential due to the large amount of agricultural waste and energy crops available in Ukraine, its contribution to the national energy system remains limited. The main obstacles are complex approval procedures for new biogas plants, a

lack of investor awareness of the economic benefits, and a lack of government support mechanisms such as subsidies and co-financing programs. In addition, the legal framework governing the development of the biogas industry is still in its infancy, and farmers and businesses have little incentive to adopt these technologies on a large scale. This regulatory uncertainty further discourages investment and slows the expansion of biogas and biomethane production.

Another key challenge is the uneven geographic distribution of energy resources. Biogas plants are mainly concentrated in the central and western regions of Ukraine, where agricultural activities are more intensive. At the same time, the eastern and southern regions of the country, where agricultural activity is lower, face difficulties in obtaining sufficient feedstock for biogas production. In addition, the situation is aggravated by the lack of adequate infrastructure for the collection and transportation of organic waste from these regions. Therefore, targeted government policies and investments in infrastructure development are required to address these regional disparities. Efforts to simplify project approval procedures and raise awareness of the benefits of biogas technology, especially in underdeveloped regions, can significantly increase the degree of integration of biogas and biomethane into the energy system of Ukraine, contributing to energy independence and sustainable development of the country.

To overcome regulatory barriers and facilitate the growth of the biogas sector, Ukraine needs to address key issues related to certification and grid access. First, a clear and effective certification process for biogas and biomethane producers should be introduced to ensure that projects meet environmental and technical standards and simplify administrative procedures for obtaining permits. This would provide greater legal certainty for investors and facilitate wider participation in the sector. In addition, Ukraine should improve the access of biogas producers to the national grid by modernising the infrastructure and creating mechanisms that will allow biogas plants to easily integrate into existing energy systems. The regulatory framework should be adapted to the unique characteristics of biogas plants, including flexibility in electricity generation and storage, so that biogas can effectively complement intermittent renewable energy sources such as wind and solar. Simplifying these regulatory processes will remove significant barriers, accelerate project implementation and increase investor confidence in the biogas industry.

The use of artificial intelligence technologies is an important factor in improving production efficiency (Iskandarov, Ismayilov, and Ismayilova, 2020). The use of AI-based optimisation algorithms allows us to automate several processes, predict the performance of biogas plants and minimise costs (Ismayilov *et al.*, 2021). AI enables more accurate analysis of raw material composition, temperature control in fermenters, and optimisation of gas purification, which significantly increases overall production efficiency. Such innovations help to increase productivity, reduce energy costs and improve plant stability.

Exchange of experience with countries that have made significant progress in biogas and biomethane technologies is key to the development of this industry. Countries such as Germany and Denmark have developed infrastructure and are successfully implementing innovative solutions in this area (Brémond *et al.*, 2020). Their experience

allows us to adopt best practices, avoid mistakes, and use proven technologies. Cooperation with international partners helps to accelerate the introduction of new technologies, increase the scale of projects and attract additional resources for the development of the industry. In general, the prospects for the development of biogas and biomethane plants are driven by a combination of economic incentives, technological innovation and international cooperation. This facilitates the integration of these technologies into the transition to clean energy, supporting sustainable development, reducing greenhouse gas emissions and reducing dependence on fossil fuels.

Discussion

The study showed that biogas and biomethane plants have great potential for the development of renewable energy in Ukraine. It has been established that the raw material base, including agricultural waste and energy crops, is capable of ensuring stable biogas production. The results confirmed the effectiveness of anaerobic digestion technologies for biogas production and the feasibility of using modern purification methods to produce high-quality biomethane. This problem was also studied by Danylyshyn and Koval (2023), whose findings confirmed that Ukraine has significant potential for the development of the biogas industry due to the abundance of agricultural waste such as manure, straw and organic materials. Due to its vast agricultural land, the country can provide the necessary feedstock for biogas plants, which reduces dependence on imported energy resources. In addition, the development of the biogas industry can contribute to reducing environmental pollution and the effective management of organic waste.

Research by Costa *et al*. (2024) also showed that anaerobic fermentation is the main technology for biogas production, which is carried out using bacteria that decompose organic materials without oxygen. A key step is the purification of biomethane from impurities such as carbon dioxide and hydrogen sulphide, which ensures high-quality gas for further use. Purification technologies include a variety of methods, including absorption and membrane filtration, which make biogas a cost-effective and environmentally friendly energy source. It is worth noting that the efficiency of biogas plants depends not only on the availability of raw materials but also on the development of infrastructure for processing and transporting organic waste. Investing in advanced technologies for anaerobic digestion and biomethane purification is an important factor in increasing the profitability of biogas projects (Korzhik, 1992). In addition, government support in the form of subsidies or soft loans can significantly accelerate the adoption of these technologies, contributing to the development of renewable energy in the country.

Engineering solutions that included the use of modular plants proved to be effective in different regions of the country. Such plants could be adapted to the specifics of raw materials and energy needs, which would reduce transportation costs and increase economic efficiency. In addition, the use of cogeneration systems ensured not only electricity generation but also efficient heat utilisation, which significantly increased overall energy efficiency. Kudria *et al*. (2023) concluded that modular biogas plants are a promising option for the development of renewable energy at the regional level in Ukraine, as they can adapt to different conditions and requirements of local

communities. Due to their compactness and adaptability, these systems can reduce installation and maintenance costs. Such installations can become an important element of local energy systems, reducing dependence on centralised energy supplies and increasing energy security.

A study by Alghorayshi *et al.* (2024) found that to achieve high efficiency of biogas plants, engineering solutions that maximise biomass utilisation and minimise energy losses are important. Optimisation of anaerobic fermentation processes and integration of biogas production with thermal systems allows for efficient use of the energy produced for heating and hot water supply. The introduction of modern technologies, such as automation and monitoring systems, can increase the reliability and productivity of biogas plants, ensuring sustainable and cost-effective production (Zhanpeisova *et al.*, 2024). These results confirm the above study, as they demonstrate a significant reduction in energy costs and an increase in production efficiency in regions with high potential for biogas energy. In addition, the use of modular biogas plants provides greater flexibility and speed of technology deployment, which contributes to the sustainability of local energy systems. Given these advantages, investment in the development of such plants could be an important step in the transition to sustainable energy in Ukraine. The integration of biogas plants into the country's energy system has been found to help stabilise electricity supply, especially when combined with other renewable sources such as solar and wind power plants. This reduced the load on the grid during peak periods, which is critical for energy security. In addition, these installations had the potential to act as backup sources of energy, compensating for the unpredictability of other renewable sources.

Notably, Bencoova *et al*. (2021) highlighted that biogas plants can play a crucial role in stabilising a country's energy system by providing a reliable and controllable energy source that compensates for the intermittent nature of solar and wind power generation. Due to their ability to operate regardless of weather conditions, biogas plants guarantee an uninterrupted fuel supply, which is important for maintaining a country's energy security. They can also be effective in times of energy shortages, reducing dependence on imported energy. In turn, Bagdadee *et al.* (2023) concluded that the integration of biogas technologies with other renewable energy sources contributes to the creation of an efficient and balanced energy system based on diverse energy sources. This makes it possible to take full advantage of the benefits of each type of renewable energy source and ensure the stability of the energy system. For example, biogas plants can compensate for the variability of solar and wind energy production, creating opportunities, together with cogeneration plants, for a continuous energy supply, even in conditions of low solar or wind activity.

This data supports the points made in the previous section, as it shows that biogas plants can play a stabilizing role in the overall energy grid of a country. Not only do they provide a stable supply of fuel for power generation during periods of reduced activity of other renewable sources, but they also help to reduce the load on traditional energy sources. This helps to increase the reliability and efficiency of the energy system, which is an important step towards energy independence and sustainable development of the country. The use of biomethane as an alternative to fossil fuels could significantly reduce greenhouse gas emissions (Fialko *et al.*, 1993). The results also show that local

biomethane production could contribute to the development of rural areas, creating new jobs and increasing the energy independence of the regions. In addition, the potential for exporting biomethane to European countries through product certification opened up new prospects for international cooperation. Sumon *et al.* (2024) also conducted a study that confirmed that the introduction of biogas plants in rural areas can significantly reduce greenhouse gas emissions, as biogas is a clean energy source that replaces the use of fossil fuels. Reducing environmental pollution has a positive impact on public health and the environment in these regions. In addition, it creates new jobs and opportunities for local economic development, which contributes to the improvement of the socio-economic situation in rural communities.

Ali *et al.* (2023) also noted that biomethane can be a key element of environmental modernisation, facilitating the transition from traditional energy sources to more sustainable and renewable ones. Due to its ability to replace natural gas, biomethane contributes to energy independence at the local level, reducing dependence on imported energy resources. Such energy autonomy is particularly important for rural areas, where the development of biogas infrastructure can become the basis for sustainable energy and economic progress. Analysing the data obtained, it can be concluded that the introduction of biogas plants in rural regions of Ukraine has great potential to reduce greenhouse gas emissions and improve the environmental situation. In addition, the results confirm that such projects have a positive impact not only on the environment but also stimulate the development of local economies, creating new jobs and increasing energy independence. Thus, the development of biogas technologies is an important step towards ensuring sustainable economic development of rural communities and strengthening energy security at the local level.

It was noted that the successful integration of such plants into the energy system required active support from the state. For example, the introduction of incentive tariffs and favourable conditions for investors significantly accelerated the development of this sector. Supporting innovations, including the introduction of artificial intelligence to optimise processes, helped to increase technology efficiency and reduce costs. Gustafsson and Anderberg (2022) concluded that government support is a key factor for the development of biogas technologies, as without adequate financial and regulatory support, these projects may not be economically viable for investors. Investments in biogas plants require significant capital investments at the implementation stage, so support in the form of subsidies or soft loans can reduce financial barriers (Shahini *et al.*, 2024). Government programmes that promote renewable energy sources can create a favourable investment environment and accelerate the transition to a sustainable energy future (Serikuly *et al.*, 2022). Catalano *et al.* (2024) found that feed-in tariffs that provide favourable conditions for biomethane producers are an effective tool to attract investment in the sector. The introduction of guaranteed tariffs for biogas products provides a stable income for enterprises, which allows them to cover the costs of technology and operations. The use of innovative approaches, such as digital technologies for monitoring and optimising processes, can further improve the efficiency of biogas plants, which is also supported by government initiatives to modernise energy infrastructure.

The analysis of the study results shows that effective state support, in particular in the form of incentive tariffs and preferential conditions for investors, is essential for the development of biogas technologies in Ukraine. Such mechanisms create a stable financial base for biogas projects, which helps to attract private investment and accelerate technological innovation in the renewable energy sector. Therefore, public policy should be focused on providing long-term incentives that will support the further development of the biogas sector as an important component of the country's energy security and environmental modernisation. Thus, the results of the study have shown that biogas and biomethane plants are strategically important for ensuring Ukraine's energy security. Their development and integration into the country's energy system create new opportunities to improve energy efficiency, stimulate economic growth and implement environmental modernisation.

To facilitate the introduction and integration of biogas technologies, Ukraine should take several effective steps. First, it could align its renewable energy policy with the standards of the EU Renewable Energy Directive (RED II), which would facilitate access to EU financing and ensure that Ukraine's biogas sector meets European regulatory sustainability criteria. Secondly, Ukraine should introduce and expand agricultural subsidies aimed at incentivising farmers to supply organic waste for biogas production, especially in regions with high agricultural production. This could include financial support for growing energy crops and waste collection infrastructure. In addition, the introduction or increase of feed-in tariffs for biogas projects would provide a stable revenue stream, making the sector more attractive to investors. Finally, the Ukrainian government should simplify permitting procedures for biogas plants, reduce bureaucratic barriers, and promote public-private partnerships to attract both local and international investment. These steps will not only increase energy security but also stimulate economic development in rural areas and contribute to the country's climate goals.

Conclusions

The study showed that biogas and biomethane plants are key elements in the development of Ukraine's energy infrastructure. They make a significant contribution to energy independence, reducing dependence on fossil fuels and supporting environmental modernisation. The analysis shows that Ukraine has a significant potential for biogas feedstock derived from agricultural wastes, food industry residues and organic materials from municipal utilities. In addition, energy crops such as corn and sorghum can provide a stable supply of feedstock.

Anaerobic fermentation technologies have proven to be highly effective for biogas production, and the integration of advanced purification techniques ensures the production of high-quality biomethane. Engineering solutions, such as modular plant designs, enable adaptation to the needs of different regions, reducing transportation costs and increasing economic efficiency. However, the introduction and integration of biogas technologies in Ukraine is strongly influenced by climatic, infrastructural and geopolitical factors. Ukraine's climate, with its seasonal fluctuations in agricultural production, affects feedstock availability, especially in regions where weather conditions disrupt crop yields. In regions with colder winters or unpredictable precipitation, the ability to maintain consistent feedstock availability may be compromised, making the

integration of energy crops even more important. In addition, Ukraine's infrastructure, especially waste management systems and the energy grid, needs to be modernised to cope with the large-scale integration of biogas production. Regions with inadequate waste collection systems or weak logistics networks may face problems in ensuring an uninterrupted supply of organic feedstock to biogas plants, which may reduce their efficiency.

Geopolitically, Ukraine's ongoing recovery from the effects of war presents both challenges and opportunities for biogas deployment. The need to reduce dependence on energy imports has become more urgent as the conflict has disrupted energy supply chains and increased demand for domestic energy sources. In this context, biogas represents a strategic solution to increase energy security, especially in rural areas where biogas production can meet local energy needs and contribute to economic recovery. However, political instability and regulatory uncertainty caused by the war may discourage foreign investment in the biogas sector and delay the necessary policy reforms.

While Ukraine has significant potential to expand biogas production, the country's progress will depend on overcoming these regional and structural challenges. Government support, infrastructure development and international cooperation are crucial to ensure the success of biogas projects and the integration of biomethane into the national energy system. Further development of biogas technologies will contribute not only to energy independence but also to environmental modernisation, helping to create a sustainable and viable energy system for Ukraine's future.

References

Alghorayshi, S.T.K., Imandoust, M., Hemmatzadeh, A., Abbasi, S., Javidfar, M., Seifollahi, M., Gitifar, S., and Zahedi, R. (2024). Design, simulation and investigation of the tri-generation process of fresh water, power and biogas using solar thermal energy and sewage sludge. *Process Saf. Environ. Prot.*, 208: 242-257. DOI: https://doi.org/10.1016/j.cherd.2024.07.009.

Ali, S., Yan, Q., Irfan, M., and Fahad, S. (2023). Relating biogas technology and environmental impact assessment: a roadmap towards clean energy for environmental sustainability. *Environ. Sci. Pollut. Res.*, 30: 72832-72853. DOI: https://doi.org/10.1007/s11356-023-27553-6.

Artemenko, Y., Zhuvahina, I., Shcherbinin, D., Yermolenko, O., and Ishchuk, O. (2025). Geographical and economic aspects of renewable energy development in Ukraine amid military threats. *Afric. J. Appl. Res.*, 11(1): 115-133. DOI: https://doi.org/10.26437/ajar.v11i1.829.

Atelge, M.R., Senol, H., Djaafri, M., Hansu, T.A., Krisa, D., Atabani, A., Eskicioglu, C., Muratçobanoğlu, H., Unalan, S., Kalloum, S., Azbar, N., and Kıvrak, H.D. (2021). A critical overview of the state-of-the-art methods for biogas purification and utilization processes. *Sustain.*, 13(20): 11515. DOI: https://doi.org/10.3390/su132011515

Bagdadee, A.H., Maitraya, A.M., Islam, A., and Siddique, M.N.E.A. (2023). A review on hybrid energy generation: Cow dung biogas, solar thermal and kinetic energy

integration for power production. *Energy Built Environ.*, 6(1): 109-120. DOI: https://doi.org/10.1016/j.enbenv.2023.09.004.

Bednarek, A., Klepacka, A., and Siudek, A. (2023). Development barriers of agricultural biogas plants in Poland. *Econ. Environ.*, 84(1): 229-258. DOI: https://doi.org/10.34659/eis.2023.84.1.528.

Bencoova, B., Grosos, R., Gomory, M., Bacova, K., and Michalkova, S. (2021). Use of biogas plants on a national and international scale. *Acta Montanist. Slovaca*, 26(1): 139-148. DOI: https://doi.org/10.46544/ams.v26i1.12.

Borisov, Y.S., Oliker, V.E., Astakhov, E.A., Korzhik, V.N., and Kunitskii, Y.A. (1987). Structure and properties of gas-thermal coatings of Fe-B-C and Fe-Ti-B-C alloys. *Sov. Pow. Metall. Metal Ceram.*, 26(4): 313-318. DOI: https://doi.org/10.1007/BF01184439.

Brémond, U., Bertrandias, A., Steyer, J., Bernet, N., and Carrere, H. (2020). A vision of European biogas sector development towards 2030: Trends and challenges. *J. Clean. Product.*, 287: 125065. DOI: https://doi.org/10.1016/j.jclepro.2020.125065.

Catalano, G., D'Adamo, I., Gastaldi, M., Nizami, A., and Ribichini, M. (2024). Incentive policies in biomethane production toward circular economy. *Renew. Sustain. Energy Rev.*, 202: 114710. DOI: https://doi.org/10.1016/j.rser.2024.114710.

Chew, K.R., Leong, H.Y., Khoo, K.S., Vo, D.N., Anjum, H., Chang, C., and Show, P.L. (2021). Effects of anaerobic digestion of food waste on biogas production and environmental impacts: A review. *Environ. Chem. Letter.*, 19(4): 2921-2939. DOI: https://doi.org/10.1007/s10311-021-01220-z.

Costa, J.M., Aguiar, A.B.S., Montanari, A.F.P., Damasceno, B.G., Duran, K.A., Jerônimo, K.A., Silva, M.M., Silva, T.C.T., and Rodriguez, R.P. (2023). Environmental aspects and perspectives of the Brazilian market for biogas and biomethane from anaerobic digestion: A review. *BioEnergy Res.*, 17(1): 59-72. DOI: https://doi.org/10.1007/s12155-023-10657-9.

Danylyshyn, V., and Koval, M. (2023). Analysis of biogas production and prospects for the development of biogas technologies in Ukraine. *Ukr. Black Sea Reg. Agrar. Sci.*, 27(3): 90-102. DOI: https://doi.org/10.56407/bs.agrarian/3.2023.90.

Dudin, V., Polehenka, M., Tkalich, O., Pavlychenko, A., Hapich, H., and Roubík, H. (2024). Ecological and economic assessment of the effectiveness of implementing bioenergy technologies in the conditions of post-war recovery of Ukraine. *Nauk. Visn. Nation. Hirn. Univ.*, 1: 203–208. DOI: https://doi.org/10.33271/nvngu/2024-1/203.

Fialko, N.M., Prokopov, V.G., Meranova, N.O., Borisov, Yu.S., Korzhik, V.N., and Sherenkovskaya, G.P. (1993). Thermal physics of gasothermal coatings formation processes. State of investigations. *Fiz. Khim. Obrabot. Mater.*, (4): 83-93. Available online at: https://shorturl.at/jjy9W (accessed on 21 March 2025).

Frankowski, J., and Czekała, W. (2023). Agricultural plant residues as potential co-substrates for biogas production. *Energ.*, 16(11): 4396. DOI: https://doi.org/10.3390/en16114396.

Gadirli, G., Pilarska, A.A., Dach, J., Pilarski, K., Kolasa-Więcek, A., and Borowiak, K. (2024). Fundamentals, operation and global prospects for the development of biogas plants – A review. *Energ.*, 17(3): 568. DOI: https://doi.org/10.3390/en17030568.

Golub, G.A., Kukharets, S.M., Yarosh, Y.D., and Kukharets, V.V. (2017). Integrated use of bioenergy conversion technologies in agroecosystems. *INMATEH Agricult. Eng.*, 51(1): 93-100. Available online at:http://ir.polissiauniver.edu.ua/bitstream/123456789/7802/1/Inmateh_51_1_2017_93-100.pdf (accessed on 21 March 2025).

Gustafsson, M., and Anderberg, S. (2022). Biogas policies and production development in Europe: A comparative analysis of eight countries. *Biofuels*, 13(8): 931-944. DOI: https://doi.org/10.1080/17597269.2022.2034380.

Hamidova, L., Huseynov, A., and Samadova, E. (2022). Challenges in Implementing Renewable Energy Sources in Azerbaijan. *Int. J. Energ. Econ. Pol.*, 12(6): 441-446. DOI: https://doi.org/10.32479/ijeep.13636.

Heiker, M., Kraume, M., Mertins, A., Wawer, T., and Rosenberger, S. (2021). Biogas plants in renewable energy systems – A systematic review of modeling approaches of biogas production. *Appl. Sci.*, 11(8): 3361. DOI: https://doi.org/10.3390/app11083361.

Hurynovich, A., Kwietniewski, M., and Romanovski, V. (2021). Evaluation of the possibility of utilization of sewage sludge from a wastewater treatment plant – Case study. *Desalin. Water Treat.*, 227: 16-25. DOI: https://doi.org/10.5004/dwt.2021.27199.

Iqbal, N., Sakhani, M.A., Khan, A.R., Atiq-Ur-Rehman, N., Ajmal, Z., and Khan, M.Z. (2021). Socioeconomic impacts of domestic biogas plants on rural households to strengthen energy security. *Environ. Sci. Pollut. Res.*, 28(21): 27446-27456. DOI: https://doi.org/10.1007/s11356-021-12633-2.

Iskandarov, E.K., Ismayilov, G.G., and Ismayilova, F.B. (2020). Diagnostic operation of gas pipelines based on artificial neuron technologies. *Adv. Intell. Syst. Comp.*, 1095: 787-791. DOI: https://doi.org/10.1007/978-3-030-35249-3_103.

Ismayilov, G.G., Iskandarov, E.K., Ismayilova, F.B., and Hacizade, S.G. (2021). Analysis of the Gas Pipelines Operation Based on Neural Networks. *Adv. Intell. Syst. Comp.*, 1306: 403-408. DOI: https://doi.org/10.1007/978-3-030-64058-3_50.

Ismayilov, V., Mammadov, S., Abbasova, N., Babayeva, V., and Sadigova, S. (2023). The current state and prospects for further development in the energy sector in Australia: reforms, foreign economic relations, investment climate. *Polit. Energ.*, 26(2): 105-120. DOI: https://doi.org/10.33223/epj/163451.

Jutteau, P. (2022). Kind of investors in renewable energies sources and territorial development. A case study on biogas in Germany. Ann de Geogr., 2022(747): 5-32. DOI: https://doi.org/10.3917/ag.747.0005.

Kabeyi, M.J.B., and Olanrewaju, O. (2022). Optimum bio-digestor design and operations. In: *Proceedings of the 5th European International Conference on Industrial Engineering and Operations Management*. Southfield: IEOM Society International. DOI: https://doi.org/10.46254/EU05.20220424.

Karaca, A.E., Dincer, I., and Nitefor, M. (2022). A unique biomass based integrated energy system for cleaner production of multiple energy outputs for sustainable communities. *Sustain. Cities Soc.*, 89: 104330. DOI: https://doi.org/10.1016/j.scs.2022.104330.

Korzhik, V.N. (1992). Theoretical analysis of the conditions required for rendering metallic alloys amorphous during gas-thermal spraying. II. Phase formation during solification of the sprayed material. *Sov. Pow. Metall. Metal Ceram.*, 31(10): 826-830. DOI: https://doi.org/10.1007/BF00797499.

Kubiczek, J., Hadasik, B., Krawczyńska, D., Przedworska, K., and Ryczko, A. (2023). Going beyond frontiers in household energy transition in Poland—a perspective. *Front. Energ. Res.*, 11: 1239115. DOI: https://doi.org/10.3389/fenrg.2023.1239115.

Kucher, O., Hutsol, T., Glowacki, S., Andreitseva, I., Dibrova, A., Muzychenko, A., Szeląg-Sikora, A., Szparaga, A., and Kocira, S. (2022). Energy Potential of Biogas Production in Ukraine. *Energ.*, 15(5): 1710. DOI: https://doi.org/10.3390/en15051710.

Kudria, S., Tarariko, Y., Kudria, N., Chernysh, Y., Chubur, V., and Roubík, H. (2023). Modelling scenarios of agricultural production development on the basis of sustainable development with the use of biogas technologies. Available online at: https://repo.btu.kharkov.ua/handle/123456789/46048 (accessed on 21 March 2025).

Lehtoranta, S., Tampio, E., Rasi, S., Laakso, J., Vikki, K., and Luostarinen, S. (2024). The implications of management practices on life cycle greenhouse gas emissions in biogas production. *J. Environ. Manag.*, 366: 121884. DOI: https://doi.org/10.1016/j.jenvman.2024.121884.

Lyubchik, S.B., Lyubchik, A.I., Lygina, E.S., Lyubchik, S.I., Makarova, T.L., Vital, J., Rego, A.M.B.d., and Fonseca, I.M. (2008). Simultaneous removal of 3d transition metals from multi-component solutions by activated carbons from co-mingled wastes. *Separat. Purific. Tech.*, 60(3): 264-271. DOI: https://doi.org/10.1016/j.seppur.2007.08.020.

Lyubchyk, A., Lygina, O., Lyubchyk, S., Fonseca, I., Tulepov, M., Mansurov, Z., and Lyubchik, S. (2015). Activated carbons from co-mingled liquid and solid organic wastes. *Euras. Chem. Tech. J.*, 17: 47-65. DOI: https://doi.org/10.18321/ectj339.

Mai-Moulin, T., Hoefnagels, R., Grundmann, P., and Junginger, M. (2020). Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II. *Renew. Sustain. Energy Rev.*, 138: 110645. DOI: https://doi.org/10.1016/j.rser.2020.110645.

Martyn, A., Novakovska, I., Medynska, N., Hunko, L., and Kolosa, L. (2024). Implementation of renewable energy sources as strategic direction for development of Ukraine's energy sector. In: Boichenko, S., Zaporozhets, A., Shkilniuk, I. and Yakovlieva, A. (eds,). *Modern Technologies in Energy and Transport II*, Cham: Springer, pp. 79-94. DOI: https://doi.org/10.1007/978-3-031-76650-3_6.

Maurus, K., Kremmeter, N., Ahmed, S., and Kazda, M. (2021). High-resolution monitoring of VFA dynamics reveals process failure and exponential decrease of biogas production. *Biomass Convers. Biorefin.*, 13(12): 10653-10663. DOI: https://doi.org/10.1007/s13399-021-02043-2.

Mignogna, D., Ceci, P., Cafaro, C., Corazzi, G., and Avino, P. (2023). Production of biogas and biomethane as renewable energy sources: A review. *Appl. Sci.*, 13(18): 10219. DOI: https://doi.org/10.3390/app131810219.

Muminova, S.S., Bayadilova, G., Mukhametzhanova, O., Seilgazina, S.M., Zhumabayeva, R., and Rvaidarova, G. (2023). The effects of feeding with organic waste by terrestrial isopod Philoscia Muscorum on enzyme activities in an incubated soil. *Euras. J. Soil Sci.*, 12(2): 122-126. DOI: https://doi.org/10.18393/ejss.1211180.

Nabgan, W., Abdullah, T.A.T., Nabgan, B., Jalil, A.A., Nordin, A.H., Ul-Hamid, A., Hassan, N.S., Hussain, I., Coelho, A., Amin, A., and Ikram, M. (2021). Catalytic biohydrogen production from organic waste materials: A literature review and bibliometric analysis. *Int. J. Hydrog. Energy*, 46(60): 30903-30925. DOI: https://doi.org/10.1016/j.ijhydene.2021.04.100.

Naumenkova, S., Tishchenko, I., Mishchenko, V., and Mishchenko, S. (2024). Rethinking energy poverty alleviation through energy efficiency: Evidence from Ukraine. *Environ. Econ.*, 15(2): 198-214. DOI: https://doi.org/10.21511/ee.15(2).2024.14.

Negro, V., Noussan, M., and Chiaramonti, D. (2024). Alternative options for biogas-to-energy: A comparison of electricity and biomethane generation based on the real operation of a production site. *Appl. Energy*, 377: 124687. DOI: https://doi.org/10.1016/j.apenergy.2024.124687.

Prussi, M., Julea, A., Lonza, L., and Thiel, C. (2020). Biomethane as alternative fuel for the EU road sector: Analysis of existing and planned infrastructure. *Energy Strat. Rev.*, 33: 100612. DOI: https://doi.org/10.1016/j.esr.2020.100612.

Rafiee, A., Khalilpour, K.R., Prest, J., and Skryabin, I. (2020). Biogas as an energy vector. *Biomass Bioenerg.*, 144: 105935. DOI: https://doi.org/10.1016/j.biombioe.2020.105935.

Rogovyi, A. (2018). Energy performances of the vortex chamber supercharger. *Energ.*, 163: 52-60. DOI: https://doi.org/10.1016/j.energy.2018.08.075.

Serikuly, Z., Markert, B., Kumisbekov, S.A., and Baratov, R.J. (2022). Recommendations for the Design of an Installation for Wind Energy Conversion into Electrical Energy. *Int. Rev. Mech. Eng.*, 16(1): 1-5. DOI: https://doi.org/10.15866/ireme.v16i1.21060.

Shahini, E., Fedorchuk, M., Hruban, V., Fedorchuk, V., and Sadovoy, O. (2024). Renewable energy opportunities in Ukraine in the context of blackouts. *Int. J. Environ. Stud.*, 81(1): 125-133. DOI: https://doi.org/10.1080/00207233.2024.2320021.

Shahini, E., Shehu, D., Kovalenko, O., and Nikonchuk, N. (2023). Comparative analysis of the main economic and biological parameters of maize hybrids that determine their productivity. *Sci. Horiz.*, 26(4): 86-96. DOI: https://doi.org/10.48077/scihor4.2023.86.

Smagulova, D.S., Rakhmetov, Y.S., Smanova, A.B., Konysbai, B., and Shansharbayeva, B. (2018). The role of the republic of kazakhstan in international legal support of energy security. *J. Environ. Manag. Tourism*, 9(7). https://journals.aserspublishing.eu/jemt/article/view/2739.

Sulewski, P., Ignaciuk, W., Szymańska, M., and Wąs, A. (2023). Development of the biomethane market in Europe. *Energ.*, 16(4): 2001. DOI: https://doi.org/10.3390/en16042001.

Sumon, N.M.F.I., Osiujjaman, N.M., Khan, N.M.A., Rahman, N.A., Uddin, N.M.K., Pant, N.L., and Debnath, N.P. (2024). Environmental and socio-economic impact assessment of renewable energy using machine learning models. *J. Econ. Finan. Account. Stud.*, 6(5): 112-122. DOI: https://doi.org/10.32996/jefas.2024.6.5.13.

Swinbourn, R., Li, C., and Wang, F. (2024). A comprehensive review on biomethane production from biogas separation and its techno-economic assessments. *ChemSusChem*, 17(19): e202400779. DOI: https://doi.org/10.1002/cssc.202400779.

Trypolska, G., Kyryziuk, S., Krupin, V., Wąs, A., and Podolets, R. (2021). Economic feasibility of agricultural biogas production by farms in Ukraine. *Energ.*, 15(1): 87. DOI: https://doi.org/10.3390/en15010087.

Wang, M., Wang, J., Li, Y., Li, Q., Li, P., Luo, L., Zhen, F., Zheng, G., and Sun, Y. (2022). Low-temperature pretreatment of biomass for enhancing biogas production: A review. *Ferment.*, 8(10): 562. DOI: https://doi.org/10.3390/fermentation8100562.

Yusuf, N., and Almomani, F. (2022). Recent advances in biogas purifying technologies: Process design and economic considerations. *Energ.*, 265: 126163. DOI: https://doi.org/10.1016/j.energy.2022.126163.

Zhanpeisova, A., Tleshova, A., Abildaeva, A., Uzbekova, D., and Abdlakhatova, N. (2024). Analysing efficiency and economic aspects in organic Rankine cycle systems. *Polit. Energ.*, 27(3): 87-108. DOI: https://doi.org/10.33223/epj/188495.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes
Collected the data	Yes	Yes	No	No	No
Contributed to data analysis & interpretation	No	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	No	No	Yes	Yes
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